PROBLEMS OF STRUCTURAL HEALTH MONITORING OF AIRCRAFT COMPONENT

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Abstract

The problems of experimental system of SHM are discussed in this article. The elements of ESHM system were designed and mounted in some zones structure and used far-field and near-field damage detection. As the objects of full-scale testing is used the helicopter MI-8 tail beam that is typical example of Al alloy structure. The ultrasonic methods were selected as a sensitive element of SHM system.

1. Introduction: SHM of a Al alloy structure of an aircraft.

This presentation is related with the European projects 6FP AISHA and 7FP AISHA II. The basic purpose of projects is development of the structural health monitoring (SHM) system integrated into a structure. Progressive methods and means of the control over use of ultrasonic technology are developed. In thin-walled structures it uses properties of elastic Lamb waves. The final stage provides carrying out of full-scale fatigue tests on components of real aviation structures for demonstration of working capacity and efficiency of methods and means of the non-destructive testing. Several different components of aircraft should be equipped by elements of the SHM systems and tested. One of the objects of full-scale testing is the MI-8 helicopter tail beam (Figure 1).

Several recent reviews discuss methods employed in detection, allocation, and evaluation of various types of structural damage [1-8]. Basically, SHM systems consist of a physical device for data collection and a signal-processing computer along with an appropriate algorithm. Efficient identification of the onset of damage at the earliest possible stage, centers on the sensitivity of a selected diagnostic parameter of structural response to the type of damage to be detected. That sensitivity is reflected in the design of the monitoring device and in the

Figure 1. Common view of the MI8 helicopter tail beam

selected signal-processing algorithm.
The MI-8 helicopter tail beam is typical Al alloy structure and has all kinds of the structural units and their connections.
The considered experimental SHM system must be able to detect any wearing damage (fatigue crack, corrosion) and any random damage, possible at operation, before it will be extended to critical size. This capability of system must be proved by direct experimental data using SHM system instrumentation, data acquisition procedures, processing algorithms and the procedure of final estimation of monitoring results. The optimal selection of the methods and equipment of NDT is second important aim of the experiment with SHM system of full-scale component.
SHM can be either active or passive. Active SHM uses active sensors that interrogate the structure to detect the presence of damage, and to estimate its extent and intensity. One active SHM method employs piezoelectric sensors, which send and receive ultrasonic Lamb waves and determine the presence of fatigue cracks and corrosions in metallic structure. Passive SHM infers the state of the structure using passive sensors that are monitored over time and fed into a structural model.
There is possibility of using combined ultrasonic methods to detect various types of induced damages on real-type structure: pulse–echo, pitch–catch and the electromechanical impedance. It is an intention to use also phased arrays technology [similar to embedded ultrasonic structural radar (EUSR)]
The pitch–catch method can be used to detect structural damages that take place between a transmitter and a receiver.
For this type of application, it seems that guided-wave pulse–echo methods are more appropriate, because wide coverage could be achieved from a single location. For crack detection with the pulse–echo method, an appropriate Lamb-wave mode must be selected.
The impedance method is a damage detection technique complementary to the wave propagation techniques.
The electromechanical impedance method is an emerging technology that offers distinctive advantage over the mechanical impedance method. Whereas the mechanical impedance method uses normal force excitation, the E/M impedance method uses in plane strain. The mechanical impedance transducer measures mechanical quantities (force and velocity/acceleration) to indirectly calculate the mechanical impedance, whereas the E/M impedance active sensor measures the E/M impedance directly as an electrical quantity.

2. Classification of structural units of the aircraft component

The MI8 helicopter tail beam (Figure 1) is the Al alloy typical structure: mainly it is thin-walled structure with joining by riveting and point-welding. Because the level of stress in a skin and others elements is relatively low, the critical sizes of possible damages (fatigue cracks) are relatively large. Therefore this structure can be accepted as fail-safe structure. It is shown that catastrophic failure of this kind of structure is not probable after partial failure of a principal structural element, and that the remaining structure is able to withstand the maximum design loads (with a specified reduced factor of safety). For SHM the structural units of aircraft components must be classified in the view to select the most convenient from available methods of monitoring. The 3-D model of the typical structure of the MI8 helicopter tail beam is shown on the Figure 2. The structural units classification are given below.

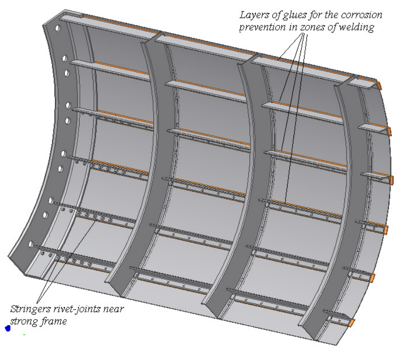


Figure 2. The typical structure of the MI8 helicopter tail beam

Group 1. Skin in regular regions (there are not exclusively powerful stresses concentrators).

ESHM must provide reliable detection of any damages within large fields of skin, using limited number of ultrasonic transducers. For the each technological sheets of them ESHM fragment must created. In this case there is a problem of damage detection on surface. The type, location and size of damage must be determined. It is the main requirement for this part of system.

Taking to the account the previous experience, the pitch–catch method can be used as a basic method to detect structural damages that take place between a transmitter transducer and a receiver transducer. The detection is performed through the examination of the guided-wave amplitude, peak-to-peak and time of flight in comparison with a "pristine" situation. At the same time, the Pulse–Echo method must be developed for this application. It seems that guided-wave pulse–echo methods are more appropriate, because wide coverage could be achieved from a single location. Therefore, at least during full-scale testing both methods should be used for damages detecting in skin. The results of comparison will allow to estimate the relative efficiency of these methods.

Group 2: Longitudinal and transversal rows of rivet -joint of sheets (Figure 3). All sheets of skin are connected between themselves by a rivet-joint. Because within surface of contact there are shear forces, the fatigue failure near rivets is possible. But from other side, all rivets of a longitudinal row are loaded approximately by the same force. Therefore the fatigue crack can occur near any rivet of row. Here there is a problem of damage detection along a line.

First solution of damage detection in this structural zone: the use of the same transducers, which are located at edges of the adjacent sheets on the opposite parties of rivet row. In this case the pitch–catch method can be used as a basic method to detect structural damages in rivet-joint. But because "sheet-sheet" can caused this method low sensitivity, the alternative pulse–echo method can be more effective. Both approach should be investigated using simple model of this kind of structural units. The problem of damage detection in transversal row of rivet -joint should be solved by similar manner.

Group 3. Typical elements of a skeleton (frames and stringers). The frame (Figure 3) is thin-walled structure (thickness 0.8-1mm) and typically contains three arc-form elements connected by riveted overlays. The wall of each frame has the cuts for stringers crossing. There are also others kinds of stress concentrator: the supports of tail propeller transmission, technological holes. As a result, the fatigue crack can be initiated by these concentrators. Special theoretical and experimental investigation needs for implementation of some rational system of damage detection in typical frames.

Figure 3. Longitudinal and transversal rows of rivet -joint of sheets

One of possible approaches is: the stresses analysis and selection of a few the most stressed zones, where damage is the most probable. In this case there is a problem of damage detection in a few points. The number of points can be less, if the reliability of defining of the places of the possible fatigue cracking is more. In individual point-shape zone the damage detection can be created using one of ultrasonic NDT methods (pitch–catch, pulse–echo or electromechanical impedance).

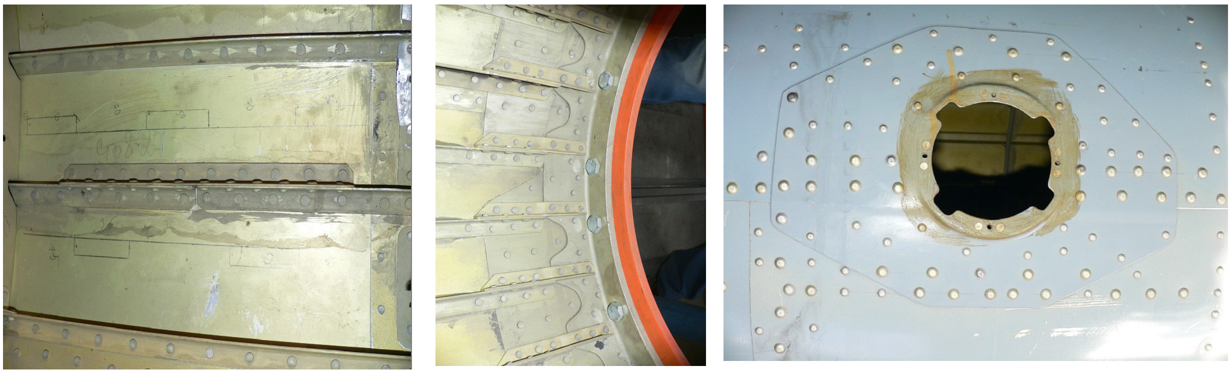
Group 4. "Hot spots" of a structure. There are many types of this kind structural unit. Some of them are shown in Figure 4. The common feature of all is a possibility to predict one or a few points of fatigue cracks occurrence. In each case, the local fragment of SHM should be created. The electromechanical impedance method of the damage detection can be preferable.

More global classification can be: 1) the far-field damage, and 2) near-field damage. In the first case the damage possible location is not known, and monitoring scheme must be: damage presence – location – sizes. In the second case the damage location can be a prior predicted, and monitoring scheme must be: damage presence– sizes.

3.Far-fields damage detection.

As mentioned above there are two types of structural units in Al alloy structure with this kind of damage. That is a sheet of skin and stringer. In latter case one coordinate defines location of damage. The pulse-echo ultrasonic method is effective mean of SHM in this case. The example of damage detecting in a stringer by this method is demonstrated by the Figure 5. The Pz27 plate 6.35 x 6.35 x 1 mm piezoceramics transducer (the demark firm In Sensor) was glued to the surface of a stringer closely to its tip (transducer t_1 on a scheme) by Electrically Conductive Adhesive EPO-TEK EE129-4. The pulse-echo technique was used for artificial damage PD (pseudo-defect) detecting. Lamb wave electronics LWDSS45 (Cedrat Technology, France) with software of Catholic University Leuven (Belgium) was used as ultrasonic wave source. The oscilloscope PXI-5105 (National Instrument) and PC consists the data acquisition system. The Figure 5 demonstrates the system response to damage appearance, then it is at distance 1500 mm from transducer. It can conclude the two transducers near tips of 5450 mm stringer are able to define the dangerous damage.

For the sheet of a skin detecting the triangulation method is the most general. The embedded ultrasonic structural radar technique [7-9] can be also effective in some cases. The pulse-echo technique similar to mentioned above is effective and low-cost version of a skin sheet, if a length of sheet is much more then a width.



a) b) c)

Figure 4. Typical “hot spots” of the structure: the technological connection of a stringer (a), the bolt-joint (b), and some hole with a forcing by riveted overlay (c)

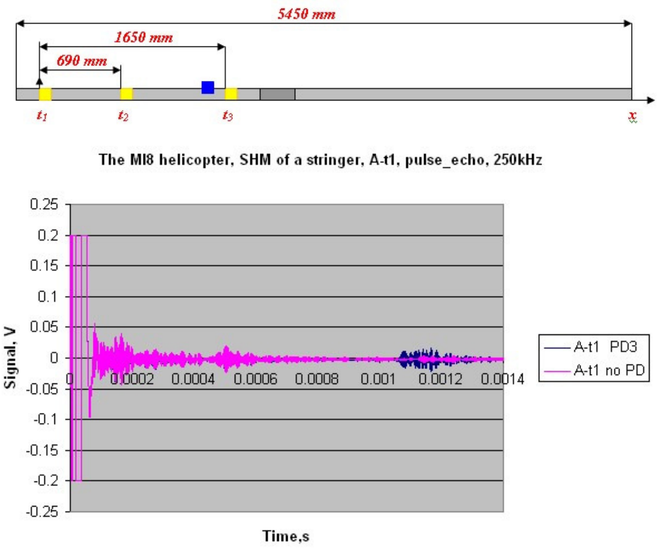


Figure 5. The damage detecting in a stringer by pulse-echo ultrasonic method

4. Near-field damage detection by a method of electromechanical impedance.

It is one of the most effective methods of the near-field damage detection. If the ultrasonic transducer is constrained, the electromechanical impedance of a system differs from this one in free state. Because the typical damages (crack, corrosion) change the local stiffness of constrain (structural element), the electromechanical impedance of transducer also changes itself. It is the theoretical base of a method.

Below the 1-D model of constrained piezoceramics transducer is developed. A type of constrained transducer is shown in Figure 6.

System of differential equations for the one-dimensional model of elastic wave propagation is:

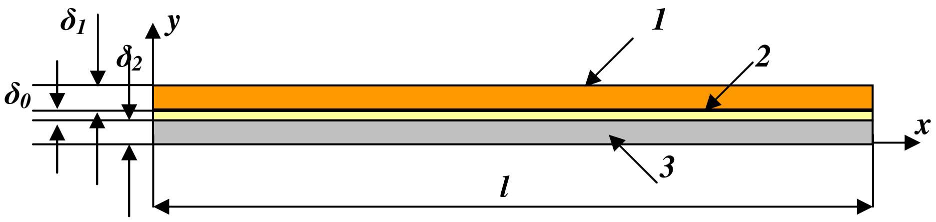


Figure 6. Piezoceramics transducer ***1*** with Al alloy overlay ***3***, glued by Epoxy past layer ***2***

$$\rho_1 A_1 \frac{\partial^2 u_1}{\partial t^2} = E_1 A_1 \frac{\partial^2 u_1}{\partial x^2} - \tau b_1 = E_1 A_1 \frac{\partial^2 u_1}{\partial x^2} - \frac{2G_1 b_1 (u_1 - u_{10})}{\delta_1} \qquad (1)$$

$$\rho_2 A_2 \frac{\partial^2 u_2}{\partial t^2} = E_2 A_2 \frac{\partial^2 u_2}{\partial x^2} + \tau b_2 = E_2 A_2 \frac{\partial^2 u_2}{\partial x^2} - \frac{2G_2 b_2 (u_2 - u_{20})}{\delta_2} \qquad (2)$$

Interlayer shear stress is

$$\tau = G_1\gamma_1 = G_2\gamma_2 = G_0\gamma_0$$

and

$$\begin{cases} \dfrac{u_1 - u_{10}}{u_{20} - u_2} = \dfrac{G_2}{G_1}\dfrac{b_2}{b_1}\dfrac{\delta_1}{\delta_2} \\ \dfrac{u_{10} - u_{20}}{u_1 - u_{10}} = 2\dfrac{G_1}{G_0}\dfrac{\delta_0}{\delta_1} \end{cases}, \qquad (3)$$

where u_i, ρ_i, E_i, G_i, A_i, b_i, δ_i are axial displacement, density, elastic modulus, shear modulus, cross-section area and its width and thickness for each layer (***i***=0,1,2).
It is supposed that axial displacement is linearly distributed along axis ***y***. Density of the glue layer is accepted equal to zero.

Equations (3) can be transformed for determination of the axial displacements u_{10} and u_{20} of the glue layer in boundary plates

$$\begin{cases} u_{10}\left(1 + \dfrac{2G_1\delta_0}{G_0\delta_1}\right) - u_{20} = \dfrac{2G_1\delta_0}{G_0\delta_1} u_1, \\ u_{10} - \left(1 + \dfrac{2G_2\delta_0}{G_0\delta_2}\right) u_{20} = -\dfrac{2G_2\delta_0}{G_0\delta_2} u_2 \end{cases} \qquad (4)$$

Finally u_{10} and u_{20} can be expressed as the function of axial displacement u_i for the layers (***i***=1,2) in next form:

$$\begin{cases} u_{10} = \beta_{11} u_1 + \beta_{12} u_2, \\ u_{20} = \beta_{21} u_1 + \beta_{22} u_2 \end{cases} \qquad (5)$$

where

$$\beta_{11} = \left[\left(1 + \frac{2G_2\delta_0}{G_0\delta_2}\right) \cdot \frac{2G_1\delta_0}{G_0\delta_1}\right] \frac{1}{D_0},$$

$$\beta_{12} = -\frac{2G_2\delta_0}{G_0\delta_2}\frac{1}{D_0}, \quad \beta_{21} = \frac{2G_1\delta_0}{G_0\delta_1}\frac{1}{D_0},$$

$$\beta_{22} = \left[\left(1 + \frac{2G_1\delta_0}{G_0\delta_1}\right) \cdot \frac{2G_2\delta_0}{G_0\delta_2}\right] \frac{1}{D_0}$$

As a result, the system of wave equations is

$$\frac{\partial^2 u_1}{\partial t^2} = c_{1(1)}^2 \frac{\partial^2 u_1}{\partial x^2} - \frac{c_{1(1)}^2 b_1}{(1+\nu_1)\delta_1 A_1}\frac{2G_2\delta_0}{G_0\delta_2 D_0}(u_1 - u_2)$$

$$\frac{\partial^2 u_2}{\partial t^2} = c_{1(2)}^2 \frac{\partial^2 u_2}{\partial x^2} + \frac{c_{1(2)}^2 b_2}{(1+\nu_2)\delta_2 A_2} \frac{2G_1\delta_0}{G_0\delta_1 D_0}(u_1 - u_2)$$

Or in dimensionless form (l is a measure unit of length)

$$\frac{l^2}{c_{1(1)}^2} \frac{\partial^2 u_1}{\partial t^2} = \frac{\partial^2 u_1}{\partial x^2} - \frac{l^2 b_1}{(1+\nu_1)\delta_1 A_1} \frac{2G_2\delta_0}{G_0\delta_2 D_0}(u_1 - u_2)$$

$$\frac{l^2}{c_{1(2)}^2} \frac{\partial^2 u_2}{\partial t^2} = \frac{\partial^2 u_2}{\partial x^2} + \frac{l^2 b_2}{(1+\nu_2)\delta_2 A_2} \frac{2G_1\delta_0}{G_0\delta_1 D_0}(u_1 - u_2)$$

Solution was accepted in a standard form:

$$u_1(x,t) = U_1(x)e^{i\omega t}, \quad u_2(x,t) = U_2(x)e^{i\omega t}$$

Finally it gives the equations system:

$$\overline{U}_1'' + \left[(\gamma_1 l)^2 - (\alpha_1 l)^2\right]\overline{U}_1 + (\alpha_1 l)^2 \overline{U}_2 = 0 \qquad (6)$$

$$\overline{U}_2'' + (\alpha_2 l)^2 \overline{U}_1 + \left[(\gamma_2 l)^2 - (\alpha_2 l)^2\right]\overline{U}_2 = 0,$$

where

$$(\alpha_1 l)^2 = \frac{l^2 b_1}{(1+\nu_1)\delta_1 A_1} \frac{2G_2\delta_0}{G_0\delta_2 D_0},$$

$$(\alpha_2 l)^2 = \frac{l^2 b_2}{(1+\nu_2)\delta_2 A_2} \frac{2G_1\delta_0}{G_0\delta_1 D_0},$$

$$(\gamma_1 l)^2 = \frac{\omega^2 l^2}{c_{1(1)}^2}, \quad (\gamma_2 l)^2 = \frac{\omega^2 l^2}{c_{1(2)}^2}$$

Solution of equations (6) is

$$\overline{U}_i(x) = B_{i1} \cos\lambda_1 x + B_{i2} \sin\lambda_1 x + B_{i3} \cos\lambda_2 x + B_{i4} \sin\lambda_2 x, \qquad (7)$$

where i=1,2 and λ_i are the value of imaginary roots of equation

$$\lambda^4 + a_1\lambda^2 + a_2 = 0 \qquad (8)$$

where

$$a_1 = (\gamma_1 l)^2 - (\alpha_1 l)^2 + (\gamma_2 l)^2 - (\alpha_2 l)^2$$

$$a_2 = \left[(\gamma_1 l)^2 - (\alpha_1 l)^2\right]\left[(\gamma_2 l)^2 - (\alpha_2 l)^2\right] - (\alpha_1 l)^2(\alpha_2 l)^2$$

Integration constants B_{ij} (j=1,2,3,4) can be defined using the boundary conditions on the tips of each layers.
If x=0 and x=l, then

$$U_1'(0) = d_{31}E_3, \quad U_1'(l) = d_{31}E_3$$

$$U_2'(0) = 0, \quad U_2'(l) = 0$$

Where d_{31} is in-plane induced strain coefficient, E_3 is the amplitude of resulting electric field.

These are the conditions for integration constants determination. As a result, the theoretical electromechanical impedance Z can be estimated by formula

$$Z = \frac{1}{i\omega C}\left[1 - k_{31}^2\left(1 - \frac{U_1(l) - U_1(0)}{d_{31}E_3}\right)\right]$$

where k_{31} is the electromechanical coupling factor, transverse to electric field, and

$C = \varepsilon_{33}^T \frac{b_1 l}{\delta_1}$ is the capacitance of the piezoceramics transducer.

The results of numerical calculation and test are demonstrated in Figures 7 and 8. The parameters of PZT PIC151 0.5x10x150mm of the firm PI was used: density 7800 kg/m^3, the in-plane modulus of elasticity $6.67 \cdot 10^7$MPa, the

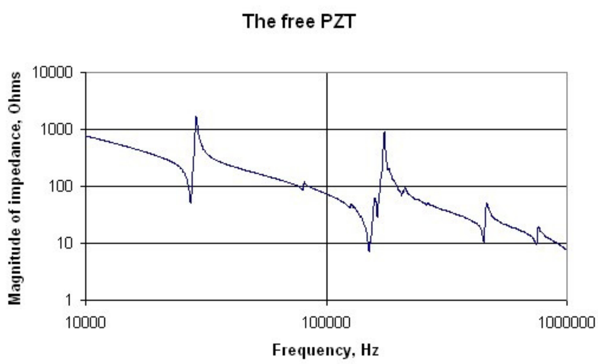


Figure 7. The electromechanical impedance magnitude of free transducer

electromechanical coupling factor $\boldsymbol{k}_{31}$ =0.38, the capacitance of the piezoceramics transducer $\boldsymbol{C}$ =2.12·10^{-8}F/m. The 0.55 mm glue layer shear modulus was 8.39· 10^{2}MPa, and it is corresponding to Epoxy Paste HYSOL EA 9309. 3NA QT SYSTEM. The Al alloy 2024-T3 1.04 mm plate was used as a constrained element.
The electromechanical impedance magnitude of free transducer is presented in Figure 7, but results of calculation and test for constrained transducer is demonstrated by Figure 8.

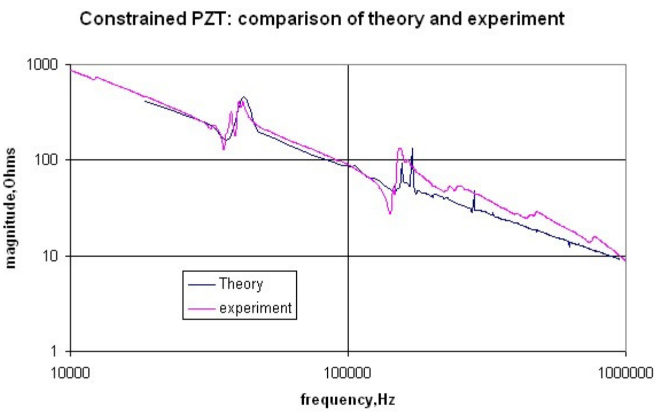


Figure 8. Comparison of the calculated and measured electromechanical impedance of constrained transducer

The important changing of spectrum of natural frequencies and value of magnitude is observed. The theoretical prediction of the PZT electromechanical impedance well corresponds to the test result. This 1-D model of constrained PZT can be used for analysis of the elastic and geometrical parameters effect to properties of piezoceramics transducer, and for structural health monitoring of element with possible near-field damage. The scheme of constraining (Figure 6) was used also for creation of a type of pre-stressed piezoceramics transducer protected from effect of mechanical fatigue and environmental degradation.

5. Conclusions

Optimization of SHM system of Al alloy structure needs a prior analysis of its properties, rational classification of structural elements and units, and selection the most effective methods of monitoring. Using ultrasonic technology the structural units rationally classifies to two groups: units with far-field and near-field damage. For first group the problem of monitoring is: damage presence-location-size determination. For second group usually there is not a problem of damage presence-location. In first case the triangulation and the phased radar methods are the most effective. In latter case the electromechanical impedance method has good perspective of effective application.
The developed 1-D model of constrained PZT can be used for analysis of the elastic and geometrical parameters effect to properties of piezoceramics transducer, and for structural health monitoring of element with possible near-field damage. The constrained piezoceramics transducer can be used for creation of a type of pre-stressed one protected from effect of mechanical fatigue and environmental degradation.

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